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6. AUTHOR(S) Michael J. Zyda, Xiaoping Yun, Eric Bachmann, and Robert B. McGhee					
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13. ABSTRACT (Maximum 200 words) A novel hybrid inertial and magnetic human body motion tracking system was developed for inserting humans into virtual environments. The system is composed of two main components: in-house designed MARG sensors and a complementary data processing filter. Each MARG sensor is a nine-axis sensor consisting of a three-axis magnetometer, a three-axis angular rate sensor, and a three-axis accelerometer, and offers one-degree accuracy, which is sufficient for human body motion tracking. The complementary filter is based on quaternions, avoiding orientation singularities associated with Euler angles, and significantly reducing the computational requirements by not using any trigonometric functions. The filter is designed to take advantage of complementary information provided by high frequency angular rate data and low frequency magnetometer and accelerometer data. A tracking system with three MARG sensors was prototyped and demonstrated. Testing results indicated that the system offers superior performance compared with commercially available products. A patent on the MARG tracking system was filed in October 2001.					
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1. Problem Statement

The objective of this research was to create a new technology for human body motion tracking in networked virtual environments. Unlike other existing body tracking technologies, this system does not depend on any external sources, thus creating a "sourceless" tracking system. The development of the new motion tracking system consists of two main components: (i) design and prototype of a novel nine-axis MARG sensor, and (ii) development and software implementation of a complimentary filter based on use of quaternions rather than Euler angles. Other components of the system development include testing and evaluation of wireless communications for transmitting sensor data, development of a realistic avatar based on laser-scanned data, and creation of a simple yet effective sensor calibration procedure.

2. Summary of the Most Important Results

2.1 Development of the MARG Sensor

Through the support of this grant, a novel hybrid inertial and magnetic sensor called MARG (Magnetic, Angular Rate, and Gravity) sensor was developed. Each MARG sensor consists of a three-axis magnetometer, a three-axis angular rate sensor, and a three-axis accelerometer. The first generation of the MARG sensor (MARG I) prototyped by the project team measured 10.1x5.5x2.5 cm (138.87 cm³) in size. Continuing effort was made to improve the sensor in a number of aspects, including reduction in size, elimination of angular rate sensor drift, incorporation of an automatic magnetic set/reset circuit, and standardization of the sensor data output. The second generation of the MARG sensor (MARG II) measured 8.4x4.2x2.9 cm (102.31 cm³) in size, a reduction of 26% in volume, and was integrated with a capacitor coupling circuit for angular rate sensor drift correction.

The operation of the MARG sensor does not depend on any signal source. It is readily operable in any location not influenced by an abnormal amount of magnetic interference. Its accuracy is within one degree, which is sufficient for human body motion tracking.

2.2 Development of a Complimentary Filter

A complimentary quaternion-based filter was developed to estimate the orientation of a rigid body to which a MARG sensor is attached. The input to the filter is nine outputs from a MARG sensor. The filter output is a quaternion representing the orientation of the body. Quaternions are used to avoid singularity in orientation representation. In theory, noiseless and unbiased rate sensor data could be integrated to determine orientation. In reality, angular rate data contain noise and tend to drift over time. As a result, angular rate data alone can be used to determine orientation for only relatively short periods of time. Gravity and the earth's magnetic field provide two fixed vectors that can be used to determine orientation. Accelerometers measure the combination of forced linear acceleration and the reaction force due to gravity. When averaged over time, an accelerometer triad can return the components of the gravity vector or the local vertical. Determination of this vector allows correction of orientation relative to a vertical axis. Similarly, magnetometers measure the

local magnetic field in body coordinates. This information is used to correct rate sensor drift errors in the horizontal plane. Thus, the vectors derived from accelerometer and magnetometer data comprise a complementary method of determining orientation.

One of the important features of the filter is the ability to continuously correct for drift without the need for still periods. This makes it possible to track a user engaged in an activity involving constant motion without a buildup of errors.

In the process of deriving the complimentary filter, a new theorem called Orthogonal Quaternion Theorem was also discovered. Application of this theorem reduces a 4×4 matrix inversion problem arising in the complementary filter to a 3×3 problem. Since matrix inversion is of order n^3 complexity, this significantly reduces the computational requirements of the filter.

2.3 Creation of a Calibration Procedure

In order for the system to operate properly, it is imperative that the null point and scale factor of each individual component of the MARG sensors be determined prior to commencing limb tracking. Unless the characteristics of the sensors themselves change, calibration need only be accomplished once. Previously, this calibration required the use of a precision tilt table and several hours of work. Practical use of a magnetic/inertial system requires a procedure that is both efficient and accurate. Through this research, a sensor calibration procedure was developed that requires only a level non-metallic surface and a compass to complete. The sensor is calibrated by placing it in the six positions which allow each accelerometer to sense gravitation acceleration in both the positive and negative directions, by subjecting each rate sensor to one or more known rotations and by rotating the MARG sensor in a manner such that maximum and minimum local magnetic field readings can be obtained for each magnetometer. The entire process requires approximately one minute to complete.

The quaternion filter algorithm allows the orientation of MARG sensor to be estimated with an accuracy of better than one degree. However, the actual goal of this research is to calculate the orientation of the limb segment to which the sensor is attached. Due to the irregular shape of human limbs it is not possible for the sensor axes to be aligned with those of the limb segment. In order to accurately track human body posture using MARG sensors, this misalignment must be corrected through the estimation of an offset. Manual estimation is both inaccurate and time consuming. To overcome this difficulty, a body model calibration algorithm was developed that allows the sensor/limb segment offsets to be calculated in a nearly instantaneous manner. Once the sensors have been attached to the limb segments, the user only need momentarily stand in a predefined position and face the local North. While this posture is being assumed all offsets are calculated. Posture tracking can then immediately commence.

2.4 Development of a Realistic Avatar

To participate in Internet communities, people need virtual representations of their bodies, called "avatars." Another effort of this project was to develop a realistic human avatar to be interfaced with the MARG sensor system. The approach taken in this project is to use a full-body laser-scanning process to capture human body surface anatomical information accurate to a scale of millimeters. Using this 3D data, virtual representations of the original human model can be simplified, constructed and placed in a networked virtual environment. The result of this project is to provide photo realistic avatars that are efficiently rendered in real-time networked virtual environments. The avatar is built in the Virtual Reality Modeling Language (VRML). Avatar motion can be controlled either with scripted behaviors using the H-Anim specification or by using real-time data from MARG sensors. Live 3D visualization of animated humanoids is viewed in freely available web browsers. This work is reported in two theses completed by James Dutton and Alper Sinav.

2.5 Integration of Wireless LAN

In the initial design, each MARG sensor is physically connected to an analog-to-digital (A/D) converter card plugged into a desktop computer by a cable. As a result, the user of MARG sensors is tethered to the vicinity of the desktop computer. An effort was made to wirelessly transmit data from the user to the desktop computer. First, a multiplexing circuit was implemented to allow tracking of 15 sensors. The output of the multiplexing circuit was connected to a wearable computer, which then digitizes the analog sensor data using a PCMCIA A/D converter and wirelessly communicates the data to the networked desktop PCs using an IEEE 802.11b spread spectrum wireless LAN. The resultant system is able to track the entire human body with 15 sensors and is untethered. The range of the system is the same as that of the wireless LAN, which can be extended with the use of repeaters. This work is reported in the thesis of Pierre Hollis.

2.6 Evaluation and Demonstration of the Body Motion Tracking System

Three MARG I sensors were initially prototyped for testing and evaluation. Performance of individual sensors was evaluated by using a precision tilt table. It was determined that MARG sensors were able to deliver accuracy of one degree or better. Next, the three sensors were used to track motion of a human arm or leg. The feasibility of tracking arm/leg motions was successfully demonstrated during the MOVES Institute's Annual Open House in August 2001.

3. List of Publications

3.1 Papers published in conference proceedings

E.R. Bachmann, I. Duman, U.Y. Usta, R.B. McGhee, X. Yun, and M.J. Zyda, "Orientation Tracking for Humans and Robots Using Inertial Sensors," Proceedings of 1999 Symposium on Computational Intelligence in Robotics and Automation, Monterey, CA, November 1999, pp. 187-194.

Eric R. Bachmann, Robert B. McGhee, Xiaoping Yun, and Michael J. Zyda, "Inertial and Magnetic Posture Tracking for Inserting Humans into Networked Virtual Environments," ACM Symposium on Virtual Reality Software and Technology (VRST'01), November 2001, Banff, Alberta, Canada, pp. 9-16.

Joao Luis Marins, Xiaoping Yun, Eric R. Bachmann, Robert B. McGhee, and Michael J. Zyda, "An Extended Kalman Filter for Quaternion-Based Orientation Estimation Using MARG Sensors," Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems, Maui, HI, Oct. 29 - Nov. 3, 2001, pp. 2003-2011.

3.2 PhD and MS theses

Joao Luis Marins, "An Extended Kalman Filter for Quaternion-Based Attitude Estimation," Engineer Degree Thesis in Electrical Engineering, Naval Postgraduate School, Monterey, CA, September 2000.

Eric R. Bachmann, "Inertial and Magnetic Tracking of Limb Segment Orientation for Inserting Humans into Synthetic Environments," PhD Dissertation, Naval Postgraduate School, Monterey, CA 93943, December 2000.

Pierre G. Hollis, "An Improved Magnetic, Angular Rate, Gravity (MARG) Body Tracking System," Engineer Degree Thesis in Electrical Engineering, Naval Postgraduate School, Monterey, CA 93943, June 2001.

James Allen Dutton, "Developing Articulated Human Models from Laser Scan Data for Use as Avatar in Real-time Networked Virtual Environments," MS Thesis in Modeling, Virtual Environments, and Simulation (MOVES), Naval Postgraduate School, Monterey, CA 93943, September 2001.

Alper Sinav, "Analysis and Modeling of the Virtual Human Interface for the MARG Body Tracking System Using Quaternions" MS Thesis in Modeling, Virtual Environments, and Simulation (MOVES), Naval Postgraduate School, Monterey, CA 93943, March 2002.

3.3 Manuscripts submitted for publication

E.R. Bachmann, R.B. McGhee, X.P. Yun, and M.J. Zyda, "Singularity Free Estimation of Rigid Body Orientation from Earth Gravity and Magnetic Field Measurements," Submitted to ACM Transactions on Graphics, April 2002.

E.R. Bachmann, R.B. McGhee, X.P. Yun, and M.J. Zyda, "Inertial and Magnetic Human Posture Tracking for Networked Virtual Environments using a Quaternion-Based Filtering Algorithm," in preparation, to be submitted to Presence in April, 2002.

E.R. Bachmann, R.B. McGhee, X.P. Yun, and M.J. Zyda, Inertial Reference Frames, and Graphics Coordinate Systems: A Resolution of Conflicting Conventions, To be submitted to the IEEE/RSJ International Conference on Intelligent Robots and Systems, April, 2002.

3.4 Technical reports

The following technical reports are available at <http://movesinstitute.org/publications.html>

Robert B. McGhee, Eric R. Bachmann, Xiaoping Yun, Michael J. Zyda, "An Investigation of Alternative Algorithms for Singularity-free Estimation of Rigid Body Orientation from Earth Gravity and Magnetic Field Measurements, " October 2001, NPS-MV-02-001.

Robert B. McGhee, Eric R. Bachmann, Xiaoping Yun and Michael J. Zyda "Real-Time Tracking and Display of Human Limb Segment Motions Using Sourceless Sensors and a Quaternion-Based Filtering Algorithm – Part I: Theory," November 2000, NPS-MV-01-001.

Eric R. Bachmann, Robert B. McGhee, Xiaoping Yun and Michael J. Zyda "Real-Time Tracking and Display of Human Limb Segment Motions Using Sourceless Sensors and a Quaternion-Based Filtering Algorithm – Part II: Calibration and Implementation," May 2001, NPS-MV-01-003

Robert B. McGhee, Eric R. Bachmann and Michael J. Zyda "Rigid Body Dynamics, Inertial Reference Frames, and Graphics Coordinate Systems: A Resolution of Conflicting Conventions and Terminology," November 2000, NPS-MV-01-002.

4. List of Participating Scientific Personnel

The following faculty participated in the project:

- Michael J. Zyda, Director and Professor of the MOVES Institute, Naval Postgraduate School.
- Robert B. McGhee, Professor of the MOVES Institute and Computer Science Department, Naval Postgraduate School.
- Xiaoping Yun, Professor of the MOVES Institute and Department of Electrical and Computer Engineering, Naval Postgraduate School.

The following personnel earned an advanced degree while participating in the project:

- Eric R. Bachmann earned his PhD degree in December 2000, and is now an Associate Professor of Computer Science at Miami University.
- Joao Luis Marins earned his Engineer Degree in September 2000.
- Pierre G. Hollis earned his Engineer Degree in June 2001.
- James A. Dutton earned his MS degree in September 2001.
- Alper Sinav earned his MS degree in March 2002.

5. Report of Inventions (by title only)

Eric. R. Bachmann, Robert B. McGhee, Xiaoping Yun, Michael J. Zyda, and Douglas L. McKinney "Method and Apparatus for Motion Tracking of an Articulated Rigid Body," US Patent, filed on October 30, 2001.